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MODERN CONTROL APPLICATIONS TO MANUAL CONTROL-HISTORICAL PERSPE--ETC(U)
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Abstract

Control theory has been applied to modeling human operator response for the past thirty years. Progress in manual control theory and applications has, therefore, been intimately dependent upon the state-of-the-art in control theory. This close relationship is particularly evident in the modeling methodology dominant during certain periods of its history. Thus, in the fifties and early sixties, classical control theory was the underlying foundation of manual control. However, with the advent of modern control theory in the late sixties and seventies, there has been an increasing application of these new tools; specifically, linear optimal control methods are utilized in characterizing human response as a controller in closed-loop regulation or tracking tasks. This paper attempts to put these developments in manual control in historical perspective. Existing methodology is assessed in terms of the practical requirements in manual control system evaluation, test and design. The merits and limitations of present methods are identified followed by an enumeration of desirable objectives and directions in future research.

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MODERN CONTROL APPLICATIONS TO MANUAL CONTROL-HISTORICAL PERSPECTIVE AND FUTURE DIRECTION

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Abstract

Control theory has been applied to modeling human operator response for the past thirty years. Progress in manual control theory and applications has, therefore, been intimately dependent upon the state-of-the-art in control theory. This close relationship is particularly evident in the modeling methodology dominant during certain periods of its history. Thus, in the fifties and early sixties, classical control theory was the underlying foundation of manual control. However, with the advent of modern control theory in the late sixties and seventies, there has been an increasing application of these new tools; specifically, linear optimal control methods are utilized in characterizing human response as a controller in closed-loop regulation or tracking tasks. This paper attempts to put these developments in manual control in historical perspective. Existing methodology is assessed in terms of the practical requirements in manual control system evaluation, test and design. The merits and limitations of present methods are identified followed by an enumeration of desirable objectives and directions in future research.

1. Introduction

The first manual control application was about thirty years ago. Since then, there have been many human operator models proposed and applied to a variety of applications. However, if a proposed model's success is measured by wide acceptance and number of applications, then there have been only two successful modeling concepts and those have remarkable similarities. The fundamental problem of quantifying human controller performance of the human interacting with control systems, continues to center on an adequate definition of a performance measure; performance measure for the system itself and certainly for the human subsystems. The future of manual control will progress to the study of training, fatigue, stress, experience, workload, and probably other issues which have been lightly passed over (or vigorously avoided) in the past. New problems will be introduced and models proposed for situations such as crew interaction and team communication where technology from decision theory, information theory, artificial intelligence and sequential machines will be employed to augment the present control theory foundation of manual control.

Supervisory control, optimization and quantification of large manned systems such as military engagements are the present trends but the underlying critical issue will be to determine performance measures for the humans and to quantify their objectives. The conclusion: experimental programs designed to determine what human controllers actually do will be the major contributors to future progress in manual control.

2. Problem Statement

Manual control is the study of a control system which has a human as at least one element in the system. A common representation is shown in Fig. 1.

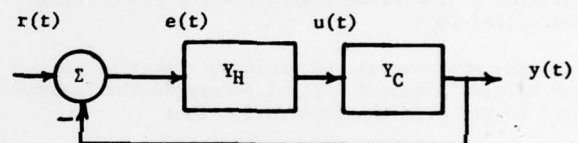


Fig. 1 A Manual Controller

The manual controller, Y_H (human operator) operates on the error signal

$$e(t) = r(t) - y(t)$$

and controls the plant, Y_C , with the output, $u(t)$, of his control effectors. The $r(t)$ input signal is the system reference and is, in general, unpredictable to the human operator.

The objective of manual control is to describe the input-output relationship across Y_H in the same terms as is used for the rest of the system. For these control system applications, control theory methods have been used to model the human operators. The resulting models have been useful in many instances but they have also been limiting as shall be demonstrated later. That is, models are used to understand something of human behavior but they are also a simplified concept of the human and, therefore, are necessarily restrictive as well.

3. Modeling the Human Controller

It has been thirty years since control theory was first applied to describe a human in a feedback control system. Tustin reported, in 1947, a

historic study which developed a quasilinear mathematical representation of a human operator in a tracking task. The work resulted from earlier work by the same author on a ground-to-air gunnery task. Probably the most recent and complete description of the quasilinear approach to manual control is contained in two publications by McRuer et al. (2,3). The first report contains experimental parameters and results and the second an overview and up-to-date description of the approach.

The structure of the quasilinear model can be represented as in Fig. 2.

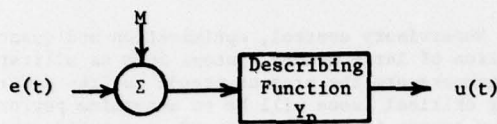


Fig. 2 Quasilinear Human Operator Model Structure

$$\text{where } Y_p = \frac{K (T_I j\omega + 1) \exp(-j\omega\tau_D)}{(T_N j\omega + 1) (T_I j\omega + 1)}$$

and η is the remnant and represents the part of the operator not linearly correlated with the system input $r(t)$. The remnant signal has been empirically determined to be a first order spectra and is a function of the error signal and the plant being controlled (3).

The most useful and profound result of the quasilinear's manual control theory is the "crossover model" with the observation that

$$Y_H Y_C = \frac{\omega_c \exp(-j\omega\tau_D)}{j\omega}$$

The crossover frequency, ω_c , and the effective time delay, τ , can be selected by a set of approximation formulas (4).

It is interesting to note that the control theory basis for quasilinear modeling also originated in the early 1940's. Classical control theory, describing function to modeling nonlinear systems, and this describing function approach to modeling human controllers are still in wide use today. However, the most confident applications of quasilinear models are in single-input/single-output, stationary, time invariant systems where remnant values are small.

The other successful modeling approach has been called "The Optimal Control Model" (5).

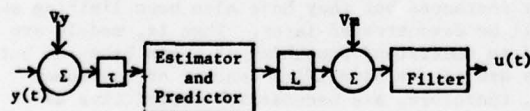


Fig. 3. Optimal Control Model Structure

where: V_y = observation noise

T = time delay

V_n = motor noise

Where the observation noise, V_y ; the time delay, τ_D and the motor noise have been determined by comparing the model to experimental data. Kleinman, et al. (6) state that these key variables of the model represent human limitations and do not depend on the parameters of the task. The estimator predictor and gain matrix, L , are found by minimizing the function

$$J + E \{ [e^2(t) + g^2(t)] dt \}$$

This model has been used in several situations and has been compared successfully to experimental data many times. The most impressive of these comparisons is probably reported in, Junker [7] where the model predicted the effect of motion on a human controller.

The model formulation in the Linear - Quadratic - Gaussian framework imposes some constraints. Selecting the utility function to be minimized is sometimes difficult and variations can be useful [8]. The parameters of the model cannot be identified uniquely from input-output experimental data [9,10] and, for some applications, it is large and perhaps more complete and precise than required. However, an interesting perspective was given by Ephraim [11] where he recorded the rapid rise in applications of the optimal control models to manual control problems; thus many are using successfully the approach.

Again, as with classical control theory, as optimal control theory became available with algorithms to solve problems in the late 1960's, it was quickly applied to the field of manual control. The reason for the emphasis on the optimal control approach at present lies in the power to handle multivariable, multi-axis, nonlinear and nonstationary stochastic control problems. These complex problems emphasize the importance of the identification and model validation issues, however.

These two successful modeling approaches have much in common: They are both based on control theory popular at the time and they are both signal processing models. Perhaps most important is that both assume fundamentally, that the humans will minimize the system error. When the human operator is behaving as a controller, he is performing a function which can be successfully modeled with a control model.

"It is only the situation in which a man is reduced to a transmission line and does no planning or prediction that his response becomes amenable to analysis by the techniques applicable to automatic controllers. At this point, and not before, it is reasonable to look for the human output variable that is a single valued function of time to be measured and analyzed and, if an input can be similarly described, perhaps entered into an equation for the human operators transfer or describing function." (12)

Thus, the determining operator's task

definition and performance measure may go considerably beyond defining the quadratic cost function of an optimal control model.

Kelly (12) gives an example which makes this point intuitively reasonable and apparent. Consider an automobile driver with the same vehicle over the same road and the same environmental conditions but with different goals:

- A. To get a woman in advanced stages of labor to a maternity hospital.
- B. To conserve gasoline, because, he may otherwise run out before he reaches a service station.
- C. To drive a visitor from out of town on a sight-seeing trip.
- D. To drive to a garage with brakes that are severely defective and may go out at any instant.
- E. To test the performance of a used car he is considering for purchase.

Driving performance in each case would be different. If the input-output signals of the driver were recorded and a model identified from the data the models would be different. What then is a "good" model for a man driving this road under the specified task situation? The issue of "performance measure" should continue to be an important question. It seems that limiting the understanding of human performance to control theory is more restrictive than necessary.

Another approach is to begin with the question, "What is the usefulness of human operators in a system?" Are the operators performing a task which can be relegated to an automatic control system? The answer is probably not. There are other elements of the task which require human attention even if the primary task is manual control. Under these circumstances a manual control model will, of course, not describe what the human is doing. The operator has a more complex performance measure than minimizing a tracking error.

The answer seems to be in the concept of a multi level control system, which would have, in addition to the standard input-output signals, information for changing the way the operator responds to inputs and outputs. Performance measures for the human would be formulated in terms of system objectives instead of tracking errors. The model would include estimates of other elements of the overall system instead of just part of the system immediately involved with the manual control task. The multi level model could be constructed by concatenating models which have already been developed to represent particular human responses (10).

A supervisory control or multi level model for humans compounds the validation and identification difficulties. On the other hand, there is the advantage of being able to formulate more

meaningful performance measures for the human subsystem. Hopefully it will avoid some of the obvious difficulties of structure limitations such as feed forward control loops to model the operator predicting signals of known form. The research can concentrate on determining what the human is doing only if the model structure is general enough to contemplate the question.

4. Conclusion

There are two useful human controller modeling techniques. Each can be employed to describe the input-output signals of humans in control tasks. There are several areas where these models can be extended, validated and additional input variables added to account for the effect of additional situations. The next big step for manual control seems to be extending the view of manual control to cover a description of performance measures and to consider the operator to be a multi level controller. This controller structure will cope with decisions, conflicting objectives, nonquadratic and "I don't care" performance functions, and other human behavior regularly observed.

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